



PHYSICS
HIGHER LEVEL
PAPER 3

Candidate session number

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SPECIMEN PAPER

1 hour 15 minutes

Examination code

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INSTRUCTIONS TO CANDIDATES

- Write your session number in the boxes above.
- Do not open this examination paper until instructed to do so.
- Section A: answer all questions.
- Section B: answer all of the questions from one of the options.
- Write your answers in the boxes provided.
- A calculator is required for this paper.
- A clean copy of the **Physics Data Booklet** is required for this paper.
- The maximum mark for this examination paper is [45 marks].

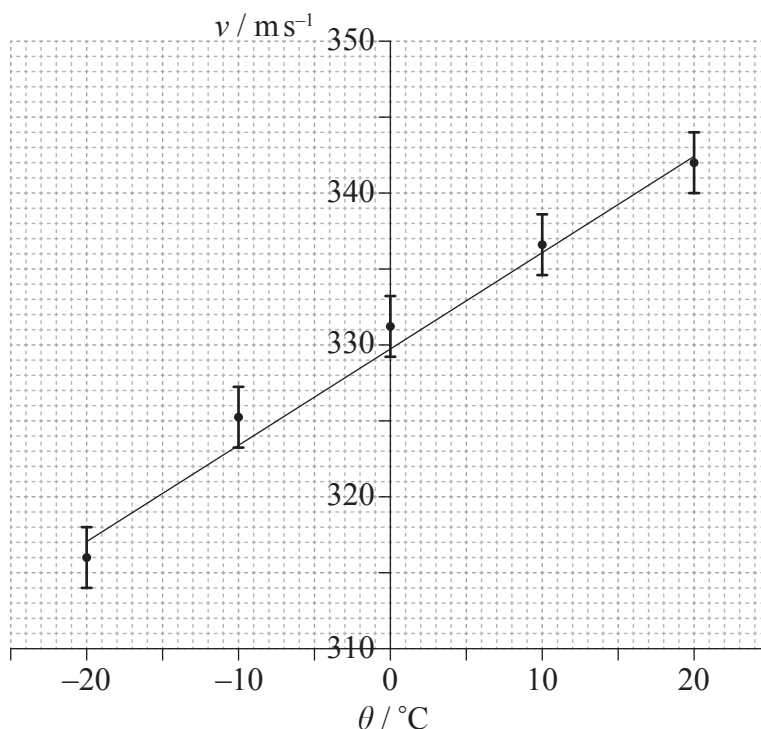
| Option | Questions |
|--------------------------------|-----------|
| Option A — Relativity | 4 – 7 |
| Option B — Engineering physics | 8 – 11 |
| Option C — Imaging | 12 – 14 |
| Option D — Astrophysics | 15 – 18 |



SECTION A

Answer **all** questions. Write your answers in the boxes provided.

1. The speed of sound in air, v , was measured at temperatures near 0°C . The graph shows the data and the line of best-fit. The error bars for temperature are too small to be shown.



A student suggests that the speed of sound v is related to the temperature θ in degrees Celsius by the equation

$$v = a + b\theta$$

where a and b are constants.

- (a) (i) Determine the value of the constant a , correct to two significant figures. [1]

(This question continues on the following page)



(Question 1 continued)

- (ii) Estimate the absolute uncertainty in b . [3]

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- (iii) A student calculates that $b = 0.593 \text{ ms}^{-1} \text{ }^{\circ}\text{C}^{-1}$. State, using your answer to (a)(ii), the value of b to the correct number of significant figures. [1]

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- (b) (i) Estimate the temperature at which the speed of sound is zero. [1]

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- (ii) Explain, with reference to your answer in (b)(i), why the student's suggestion is not valid. [2]

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2. A student uses an electronic timer in an attempt to estimate the acceleration of free-fall g . She measures the time t taken for a small metal ball to fall through a height h of 0.50 m. The percentage uncertainty in the measurement of time is 0.3 % and the percentage uncertainty height is 0.6 %.

- (a) Using $h = \frac{1}{2}gt^2$, calculate the expected percentage uncertainty in the value of g . [1]

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- (b) State and explain how the student could obtain a more reliable value for g . [3]

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3. In an experiment to measure the specific heat capacity of a metal, a piece of metal is placed inside a container of boiling water at 100°C . The metal is then transferred into a calorimeter containing water at a temperature of 10°C . The final equilibrium temperature of the water was measured. One source of error in this experiment is that a small mass of boiling water will be transferred to the calorimeter along with the metal.

- (a) Suggest the effect of the error on the measured value of the specific heat capacity of the metal. [2]

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- (b) State **one** other source of error for this experiment. [1]

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SECTION B

Answer *all* of the questions from *one* of the options. Write your answers in the boxes provided.

Option A — Relativity

4. (a) Einstein discovered a discrepancy, related to the speed of light, between Maxwell's equations of electromagnetism and Newtonian mechanics. Outline the discrepancy and how Einstein dealt with it. [2]

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(Option A continues on the following page)



(Option A, question 4 continued)

- (b) A proton enters a region of uniform magnetic field which is directed into the plane of the page as shown.



Reference frame S is at rest with respect to the magnetic field. The speed of the proton is measured to be v in S .

- (i) State the nature of the force on the proton according to an observer in S . [1]

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- (ii) S' is a reference frame in which the proton is at rest. State and explain whether, according to an observer in S' , there is a force on the proton. [2]

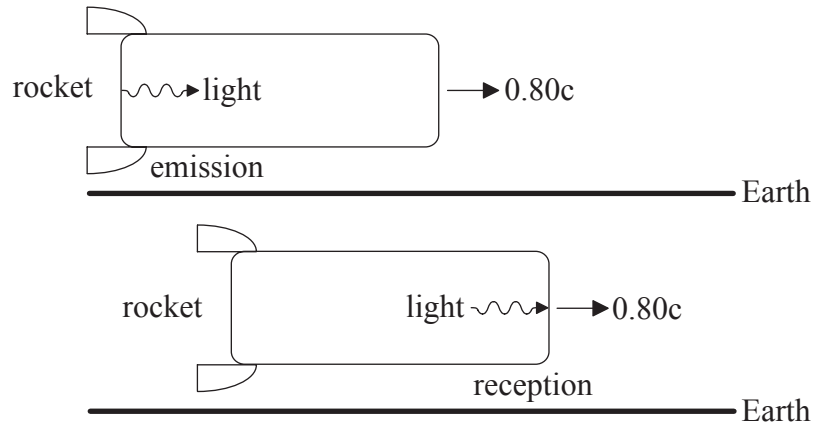
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(Option A continues on the following page)



(Option A continued)

5. A rocket of proper length 900 m is moving at speed $0.80c$ relative to the Earth. E is a reference frame in which the Earth is at rest. R is a reference frame in which the rocket is at rest. The diagram is from the point of view of E.



- (a) A light signal is emitted from the back of the rocket and is received at the front of the rocket.

Determine the

- (i) time interval between the emission and reception of the light signal according to an observer in R. [1]

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- (ii) time interval between the emission and reception of the light signal according to an observer in E. [3]

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(Option A continues on the following page)



(Option A, question 5 continued)

- (iii) distance separating the emission and reception of the light signal according to an observer in E.

[1]

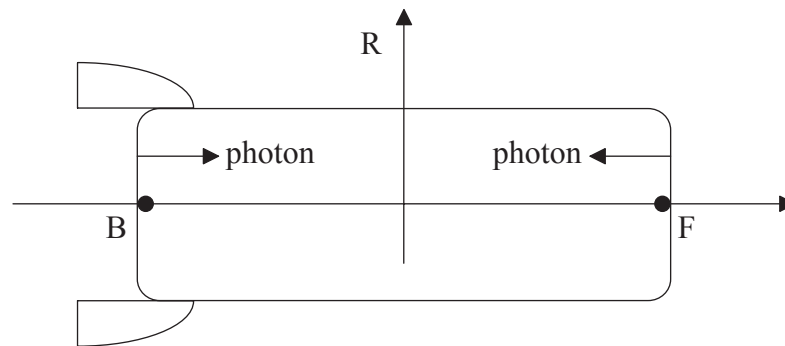
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(Option A continues on the following page)



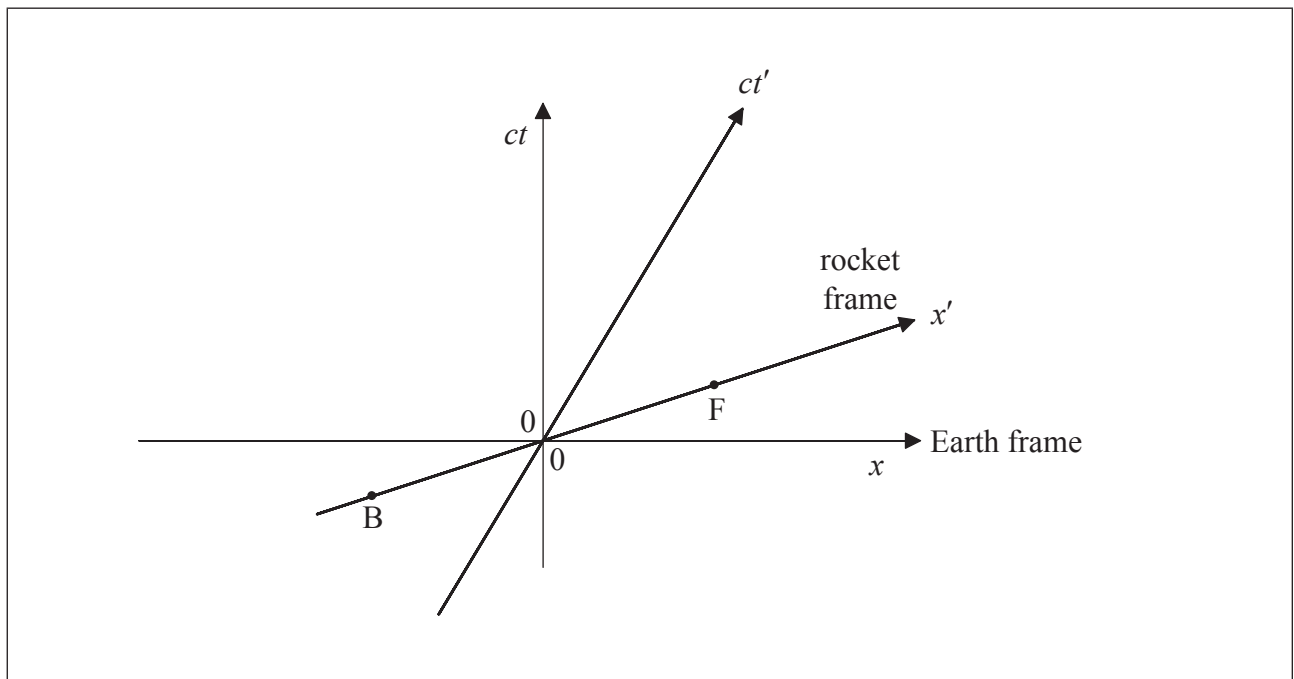
(Option A, question 5 continued)

- (b) One photon is emitted from the back B of the rocket and another photon is emitted from the front F of the rocket, as shown.



The emissions are simultaneous according to observers in R. The photons are received by an observer at rest in the middle of the rocket.

The spacetime diagram represents the reference frame of the Earth E and the rocket frame R. The coordinates in frame E are x and ct and in frame R they are x' and ct' . The position of the back B and of the front F of the rocket at $t' = 0$ are labelled. The origin of the axes corresponds to the middle of the rocket.



- (i) On the spacetime diagram, draw lines to show the worldlines of the photons from when they were emitted to when they were received.

[3]

(Option A continues on the following page)



(Option A, question 5 continued)

- (ii) Using the spacetime diagram, determine which photon was emitted first according to observers in E. [2]

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- (iii) Determine the time separating the emissions of the two photons according to observers in E. [2]

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- (c) A missile is launched from the rocket. The velocity of the missile is $-0.62c$ relative to the rocket. Calculate the velocity of the rocket relative to the Earth. [3]

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(Option A continues on the following page)



(Option A continued)

6. A neutral pion (π^0) has total energy 1070 MeV as measured by observers in a laboratory. The pion decays in a vacuum into a pair of photons according to the following.

$$\pi^0 \rightarrow \gamma + \gamma$$

Photon X is emitted in the direction of the velocity of the pion and photon Y is emitted in the opposite direction. The rest mass of the pion is $m = 135 \text{ MeV c}^{-2}$.

- (a) Show that the momentum of the pion is 1060 MeV c^{-1} . [1]

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- (b) The energy of photon X is E_X and the energy of photon Y is E_Y . Using the laws of conservation of total energy and momentum, calculate E_Y . [3]

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(Option A continues on the following page)



(Option A continued)

7. (a) (i) State the equivalence principle.

[1]

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(ii) Explain, using the equivalence principle, the phenomenon of gravitational redshift. [3]

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(Option A continues on the following page)



Turn over

(Option A, question 7 continued)

- (b) A clock is placed at a distance r from the centre of a black hole of radius R_s such that $\frac{r}{R_s} = 1.25$.

The clock ticks once every second according to stationary observers next to the clock. Calculate the time between ticks of this clock according to observers far from the black hole.

[2]

End of Option A



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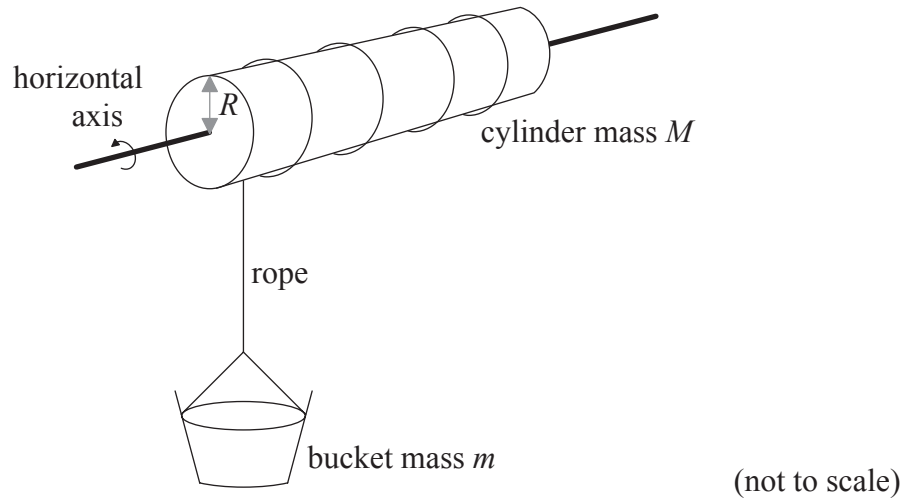


405D15

Turn over

Option B — Engineering physics

8. A bucket of mass m is held above a water well by a rope of negligible mass, as shown. The rope is wound around a cylinder of mass M and radius R . The moment of inertia of the cylinder about its axis is $I = \frac{1}{2}MR^2$.



The bucket is released from rest. Resistance forces may be ignored.

- (a) Show that the acceleration a of the bucket is given by the following equation.

$$a = \frac{mg}{m + \frac{M}{2}} \quad [4]$$

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(Option B continues on the following page)



(Option B, question 8 continued)

(b) The following data are available.

Bucket mass $m = 24 \text{ kg}$
 Cylinder mass $M = 36 \text{ kg}$
 Radius $R = 0.20 \text{ m}$

(i) Calculate the speed of the bucket when it has fallen a distance of 16 m from rest. [2]

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(ii) Calculate the rate of change of the angular momentum of the cylinder. [3]

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(c) The bucket in (b) is filled with water so its total mass is now 45 kg. The bucket is raised at a constant speed of 2.0 m s^{-1} using an electric motor attached to the cylinder. Calculate the power output of the motor. [1]

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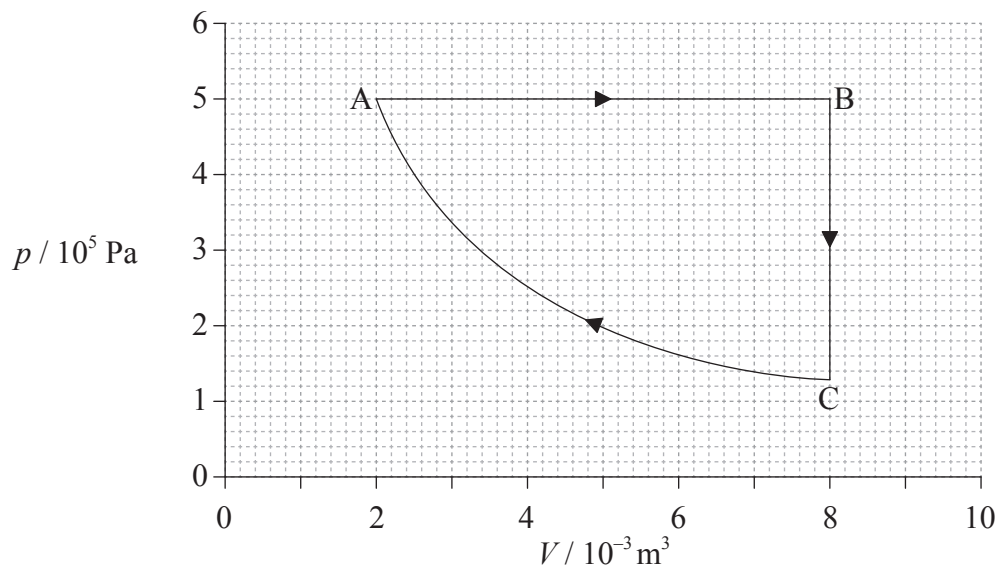
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(Option B continues on the following page)



(Option B continued)

9. The pressure volume (pV) diagram shows a cycle ABCA of a heat engine. The working substance of the engine is a fixed mass of an ideal gas.



The temperature of the gas at A is 400 K.

- (a) Calculate the maximum temperature of the gas during the cycle.

[1]

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(Option B continues on the following page)



(Option B, question 9 continued)

(b) For the isobaric expansion AB, calculate the

(i) work done by the gas. [2]

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(ii) change in the internal energy of the gas. [1]

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(iii) thermal energy transferred to the gas. [1]

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(Option B continues on the following page)



(Option B, question 9 continued)

- (c) The work done on the gas during the isothermal compression is 1390 J. Determine the change in entropy of the gas for this compression. [2]

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- (d) Determine the efficiency of the cycle ABCA. [2]

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- (e) State whether the efficiency of a Carnot engine operating between the same temperatures as those operating in cycle ABCA on page 18, would be greater than, equal to, **or** less than the efficiency in (d). [1]

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(Option B continues on page 22)



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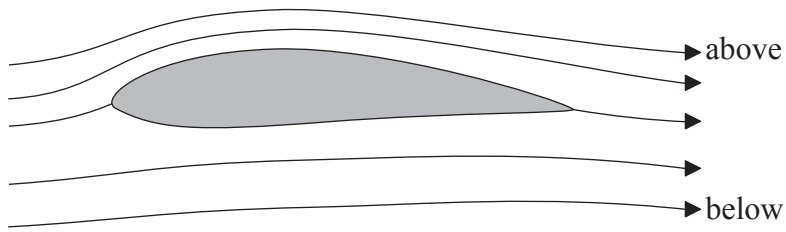


405D24

Turn over

(Option B continued from page 20)

10. The diagram shows streamlines past an airfoil that is placed in a stream of air. The flow is laminar.



- (a) State what is meant by laminar flow.

[1]

(Option B continues on the following page)



(Option B, question 10 continued)

- (b) (i) The streamlines above the airfoil are closer to each other than the streamlines below the airfoil. Suggest why this implies that the speed of the air above the airfoil is greater than the speed of air below the airfoil. [2]

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- (ii) The speed of air above the airfoil is 64 m s^{-1} and the speed of air below the airfoil is 52 m s^{-1} . The density of air is 0.95 kg m^{-3} . The areas of the upper and lower surfaces of the airfoil are both effectively 2.0 m^2 and the airfoil is very thin. Determine the lift on the airfoil. [3]

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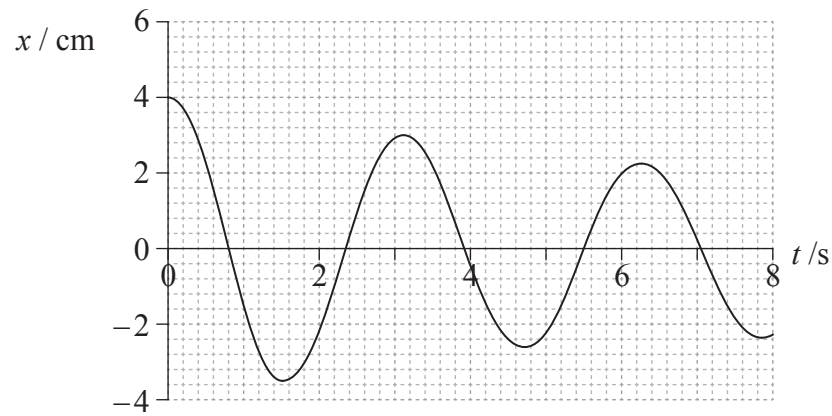
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(Option B continues on the following page)



(Option B continued)

11. A spring performs damped harmonic oscillations. The graph shows the variation with time t of the displacement x of the spring.



- (a) Estimate the Q factor of the spring.

[2]

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(Option B continues on the following page)



(Option B, question 11 continued)

- (b) The damped spring is now subjected to an external periodic driving force whose frequency is close to the natural frequency of the spring.

Suggest the effect, if any,

- (i) of this force on the steady-state amplitude of oscillations of the spring. [1]

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- (ii) on the phase difference between the driven and the driving systems. [1]

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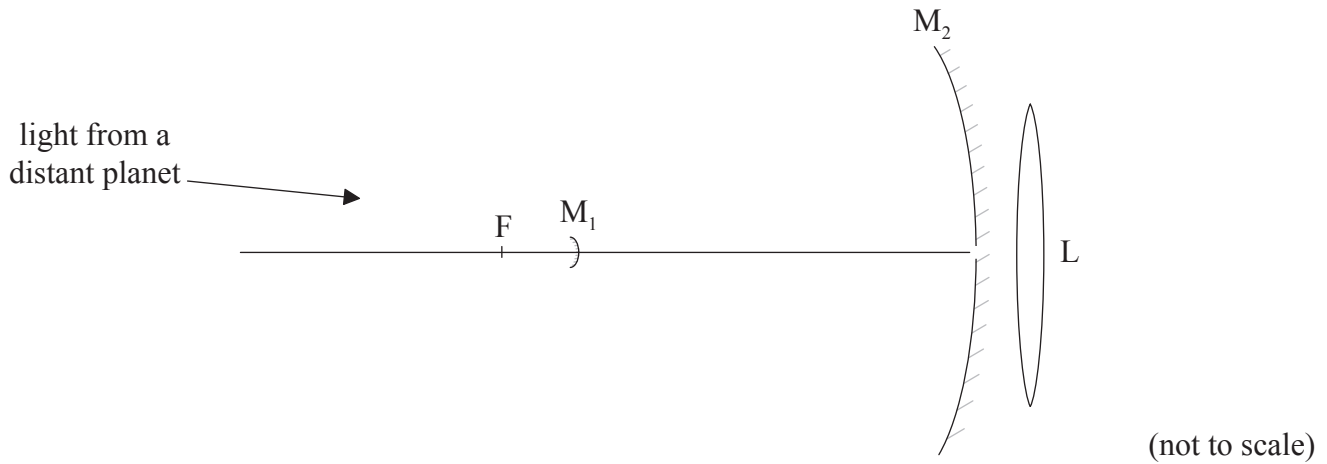
End of Option B



Turn over

Option C — Imaging

12. (a) The diagram shows a Cassegrain reflecting telescope consisting of a small diverging mirror M_1 , a large converging mirror M_2 , and a converging lens L . The focal point of M_2 is at F .



The telescope is used to view a planet. The diameter of the planet subtends an angle of 1.40×10^{-4} rad at M_2 . The focal length of M_2 is 9.50 m.

- (i) Show that the diameter of the image of the planet that would be formed by M_2 alone is 1.33 mm. [3]

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(Option C continues on the following page)



(Option C, question 12 continued)

- (ii) M_1 is at a distance of 8.57 m from the aperture of M_2 . The image in (a)(i) now serves as a virtual object for M_1 . A real image is formed at the opening of M_2 . Show that the diameter of this image is 12.0 mm. [3]

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- (iii) The real image in (a)(ii) is now viewed by L of focal length 98.0 mm. The final image of the planet is formed at infinity. Calculate the overall magnification of the telescope. [3]

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(Option C continues on the following page)



(Option C, question 12 continued)

- (b) (i) The large concave mirror in most reflecting telescopes is parabolic rather than spherical. Suggest **one** reason for this. [1]

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- (ii) State **one** advantage of reflecting telescopes compared to refracting telescopes. [1]

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- (c) Telescopes available today include, in addition to optical telescopes, infrared, radio, ultraviolet and X-ray telescopes. Outline how the introduction of these telescopes has changed our view of the universe. [2]

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(Option C continues on the following page)



(Option C continued)

13. (a) A compound microscope has an objective lens of focal length 0.40 cm and an eyepiece lens of focal length 3.20 cm. The image formed by the objective is 0.20 m from the objective lens. The final image is formed at a distance of 25 cm from the eyepiece lens.

- (i) Show that the position of the object is 4.1×10^{-3} m from the objective lens. [1]

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- (ii) Determine the angular magnification of the microscope. [2]

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- (iii) The smallest distance between two points that can be distinguished by an unaided human eye from a distance of 25 cm is approximately 0.1 mm. Calculate the smallest distance between two points that can be distinguished using this microscope. [1]

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(Option C continues on the following page)



(Option C, question 13 continued)

- (b) The images from the microscope are digitized and transmitted along an optic fibre. The input power of the signal is 120mW and the attenuation per unit length of the optic fibre is 6.2 dB km^{-1} . The length of the fibre is 4.6km. Calculate the output power of the signal. [3]

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14. (a) One of the factors affecting the quality of an X-ray image is sharpness.

- (i) Outline what is meant by sharpness. [1]

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- (ii) State **one** way in which the sharpness of an X-ray image may be improved. [1]

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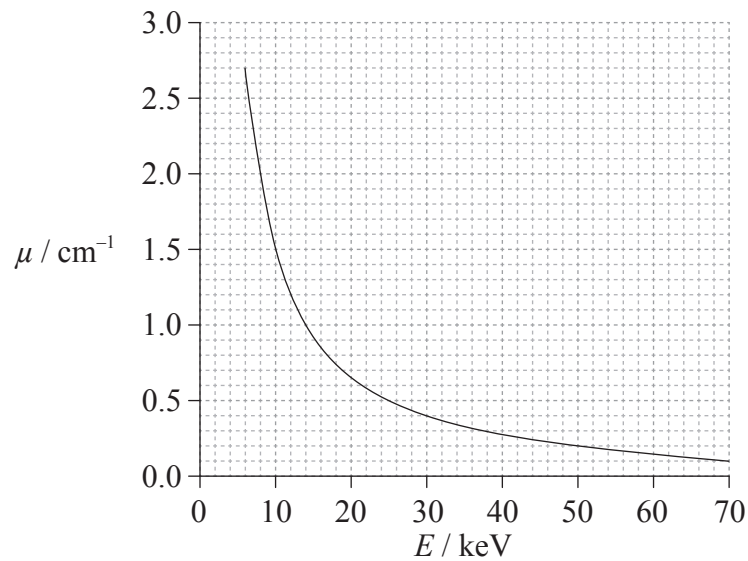
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(Option C continues on the following page)



(Option C, question 14 continued)

- (b) The graph shows how the linear absorption coefficient μ , for tissue, varies with photon energy E .



- (i) Suggest why it is desirable to remove the low-energy photons from the beam. [1]

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- (ii) Determine, for X-rays of energy 50 keV, the percentage of the incident intensity that is transmitted through a tissue section of thickness 2.0 cm. [2]

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(Option C continues on the following page)



(Option C, question 14 continued)

(c) Explain, in the context of magnetic resonance imaging (MRI), the role of the

(i) radio frequency (RF) signal.

[1]

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(ii) gradient field.

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(iii) proton spin relaxation time.

[1]

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(d) State **two** advantages of using MRI rather than X-rays for imaging the brain.

[2]

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End of Option C



Option D — Astrophysics

15. (a) State the element which is the end product of nuclear reactions taking place inside main sequence stars. [1]

- (b) A main sequence star has apparent brightness $7.6 \times 10^{-14} \text{ W m}^{-2}$ and luminosity $3.8 \times 10^{27} \text{ W}$.

- (i) Calculate, in pc, the distance of the star from Earth. [3]

- (ii) Suggest whether the stellar parallax method is appropriate for measuring the distance to this star. [1]

- (iii) The luminosity of the star in (b) is ten times the luminosity of our Sun.

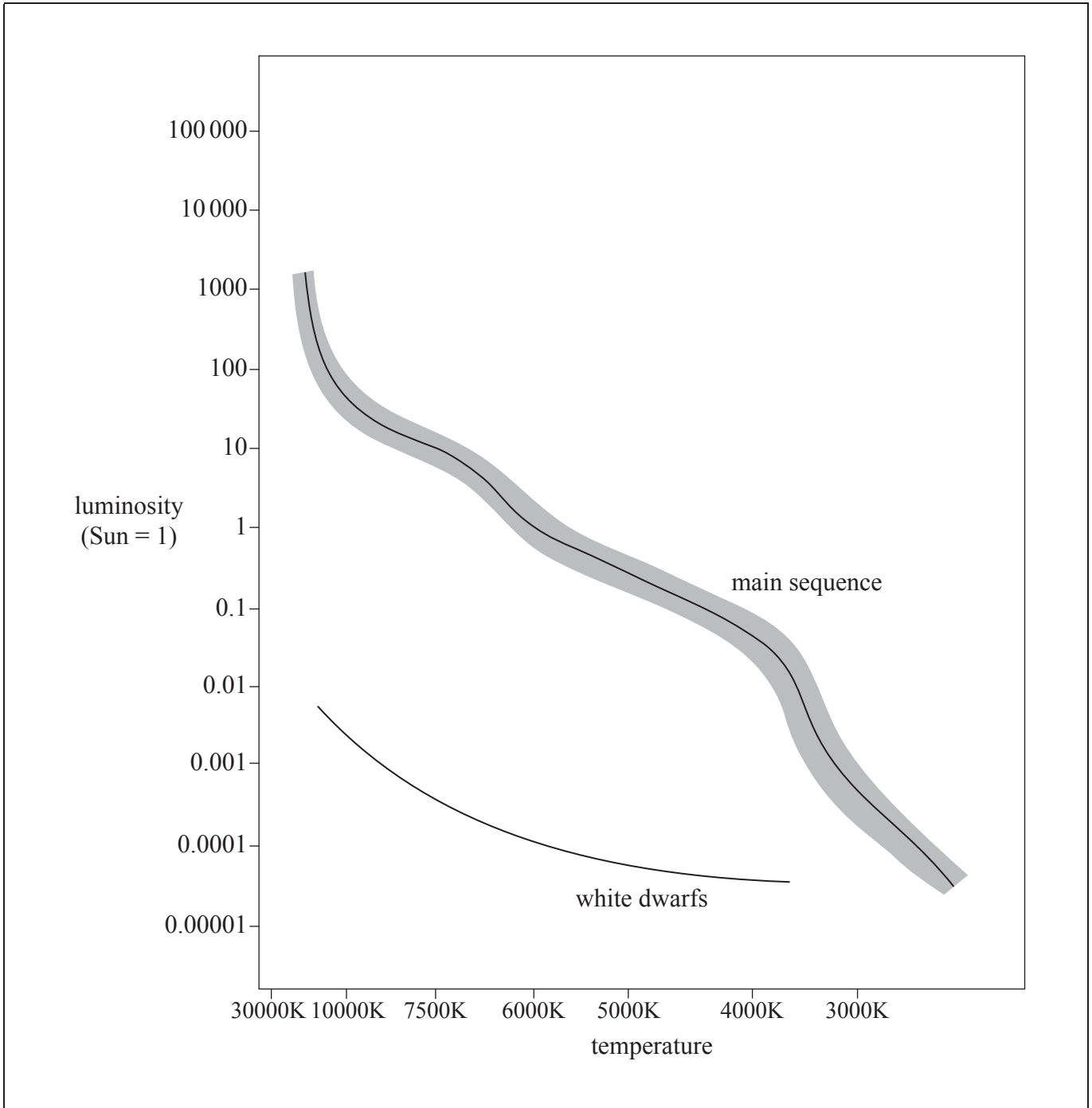
Determine the ratio $\frac{M}{M_{\odot}}$ where M_{\odot} is the mass of the Sun. [2]

(Option D continues on the following page)



(Option D, question 15 continued)

(c) The image shows a Hertzsprung–Russell (HR) diagram.



(Option D continues on the following page)



(Option D, question 15 continued)

- (i) Estimate, using the HR diagram, the ratio $\frac{R}{R_{\odot}}$ where R is the radius of the star in (b) and R_{\odot} is the radius of the Sun. [3]

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- (ii) Sketch a line on the HR diagram to show the evolutionary path of this star. [2]

- (iii) Describe, with reference to the Chandrasekhar limit, the equilibrium state of this star in its final evolutionary stage. [2]

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(Option D continues on the following page)



(Option D continued)

16. (a) The hydrogen spectrum from a laboratory source includes a line of wavelength 434 nm. The same line emitted from a distant galaxy has wavelength 502 nm when observed on Earth.

- (i) Suggest why the two wavelengths are different. [1]

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- (ii) Determine the distance, in Mpc, from this galaxy to Earth using a Hubble constant of $71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. [2]

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(Option D continues on the following page)



(Option D, question 16 continued)

- (b) In the 1990s, two research groups started projects involving observations of distant supernovae. They aimed to show that distant galaxies were slowing down.

- (i) Suggest why it was expected that distant galaxies would be slowing down. [1]

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- (ii) Describe how it was deduced that the universe is expanding at an accelerated rate. [2]

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(Option D continues on the following page)



(Option D continued)

17. (a) Suggest why nuclear fusion processes inside stars can only produce elements with a nucleon (mass) number up to about sixty. [2]

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- (b) Outline how elements of nucleon (mass) number higher than sixty are produced by stars. [2]

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(Option D continues on the following page)



(Option D continued)

18. (a) Measurements by WMAP have revealed very small deviations from isotropy in the cosmic microwave background (CMB) radiation. Suggest why it was important that the CMB should not be perfectly isotropic. [2]

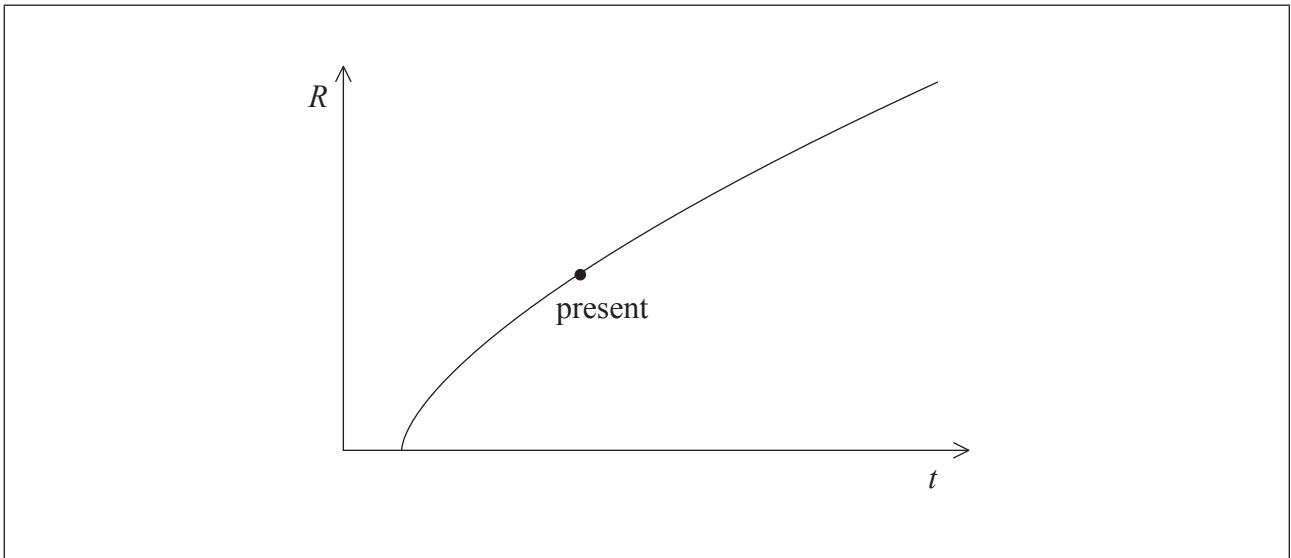
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- (b) Another WMAP result is that the universe is flat. The graph shows how the scale factor of the universe R , varies with time t in a flat universe **without** dark energy.



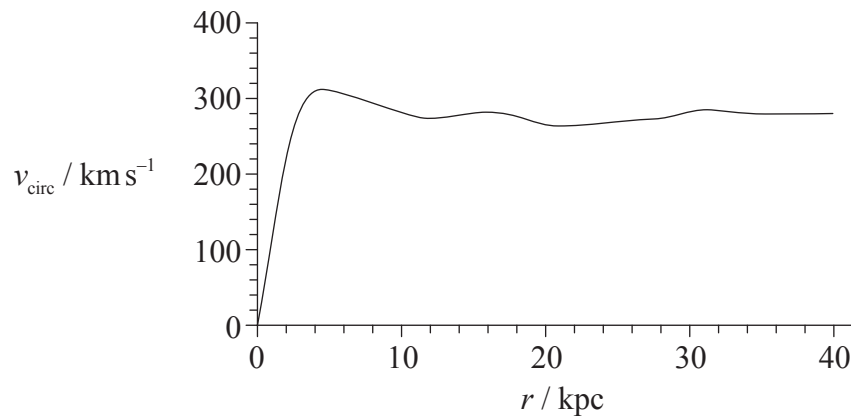
Using the axes, draw a curve to show how the scale factor varies with time in a flat universe **with** dark energy. [1]

(Option D continues on the following page)



(Option D, question 18 continued)

- (c) The graph shows the variation of the rotational speeds of stars v_{circ} with distance r from the center of a galaxy.



- (i) State the feature of the graph that indicates the existence of dark matter. [1]

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- (ii) Explain how the feature you stated in (c)(i) indicates the existence of dark matter. [2]

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End of Option D

